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IMPROVE LIDAR PERFORMANCE WITH UV DURABLE HYDROPHOBIC COATINGS

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ABSTRACT

Autonomous driving is emerging as the future of transportation recently. For autonomous driving to be safe and reliable the perception sensors need sufficient vision in sometimes challenging operating conditions including dust, dirt, and moisture or during inclement weather. LiDAR perception sensors used in certain autonomous driving solutions require both a clean and dry sensor screen to effectively operate in a safe manner. In this paper, UV durable Hydrophobic (UVH) coatings were developed to improve LiDAR sensing performance. A lab testbed was successfully constructed to evaluate UVH coatings and uncoated control samples for LiDAR sensor under the simulated weathering conditions, including fog, rain, mud, and bug. In addition, a mobile testbed was developed in partnership with North Dakota State University (NDSU) to evaluate the UVH coatings in an autonomous moving vehicle under different weathering conditions. These UV-durable easy-to-clean coatings with high optical transmission, good wear durability, and excellent UV durability could improve the effectiveness and efficiency of the LiDAR sensor, which provides a key improvement in safety for autonomous vehicles.

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1. INTRODUCTION

Autonomous vehicles (AVs) utilize multiple sensor devices, like high-resolution cameras and radar sensors, to interpret the driving environment and achieve full autonomy. One of these instruments, the light detection and ranging (LiDAR) sensor, utilizes pulsed infrared (IR) light, typically at wavelengths of 905 nm or 1,550 nm. The LiDAR sensor receives the reflected light from objects and calculates each object's distance and position.

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Unlike cameras or radar sensors, LiDARs are not located behind the windshield or bumpers, they must be mounted on an exterior surface without obstructions. In a field operation, exterior lenses of LiDAR sensors or enclosures usually will be covered with dirt, bugs, bird excrement, and other debris. That dirt or even the rain streaks on LiDAR lenses will reduce the detection intensity and probability of detection due to the partial blockage or partial refraction reducing output and received signal strength. As a result, keeping LiDARs clean and dry is crucial to the operation of an AV.

Valeo [1] and Continental [2] have developed fully automatic cleaning systems for AV LiDARs and cameras. The technologies use retractable liquid-jet nozzles that spray a precise amount of cleaning fluid which is stored in an onboard reservoir onto the sensor lens or face. Ford's [3] AV development team has built a set of aerodynamic shields for installation on the roofs of Ford's self-driving prototype fleet. The devices create air currents that deflect bugs from the rooftop LiDAR sensors. Innovasonic, Inc. [4] has developed an active self-cleaning process based on ultrasonic vibration. The process utilized mechanical vibration to break up the debris on the lens surface and remove them without using the cleaning fluid.

However, these additional cleaning systems may incur significant costs to the AVs, including installation and future repair. A UV durable hydrophobic self-cleaning coating that repels dirt and rain may be an ideal alternative on LiDAR surface to reduce the active cleaning cycles and minimize cleaning fluids or energy consumption.

One of the most challenging aspects of preparing hydrophobic coatings for the LiDAR system is to maintain a good degree of transparency while retaining scratch-resistant, and robust UV resistant self-cleaning and stain-free characteristics.

Many efficient methods of producing transparent non-wettable surfaces have been demonstrated. Some of the materials are fabricated by self-assembly methods, including sol-gel processes, micro-phase separation, templating, and nanoparticle assembly [5, 6, 7, 8, 9]. Some of the transparent and non-wettable materials are obtained by various mold transfer processes including nanoimprint lithography which utilizes hydrophobic transparent elastomer precursors or others with UV-induced polymerization [10, 11, 12]. Some of the films are ceramic precursor-based transparent non-wettable coatings that are deemed suitable for windows or solar energy conversion unit surfaces [13, 14, 15]. Most of these methods are still not suitable for sustained UV durability and mechanical durability against abrasion-induced wear due to the inadequate adhesion between the films and the substrates, and poor scratch-resistance of the film itself.

Lu. et al. [16] recently developed a solvent-based thermal curing hydrophobic and oleophobic coating consisting of fluorinated silane, which is designed for smartphones, tablets, and touch screen laptops. This hydrophobic coating demonstrated high optical transmission with excellent wear durability by passing 10,000 cycles using #0000 steel wool under a 1 kg load. However, the coating did not show good UV durability against extensive UV irradiation, which makes this coating not suitable as an exterior coating for in-field operations.

To improve the UV-durability and maintain the high optical transmission with good wear durability, a new coating system was proposed and developed as a UV durable Hydrophobic (UVH) coating. Its UV durability and hydrophobicity were evaluated with 3000 hours in ASTM D7869 Weather-O-Meter (WOM) testing followed by the static water contact angle measurement. A lab testbed was constructed to evaluate

LiDAR performances with and without the UVH coatings under the simulated weathering environment, including fog, rain, mud, and bug conditions. In addition, a mobile testbed was developed in partnership with North Dakota State University (NDSU) to evaluate the UVH coatings in an autonomous moving vehicle under different weathering conditions.

2. UV DURABLE HYDROPHOBIC (UVH) COATINGS

UVH coating is a solvent-based thermal curing hydrophobic and oleophobic coating. The developed UVH coating solution from PPG Industries, Inc. was sprayed using an ultrasonic spray system Prism Ultra-Coat (Ultrasonic Systems, Inc., Haverhill, MA) after pre-treating the polycarbonate substrate using a low-pressure plasma system (Diener Electronics, GmbH, Germany). The samples were then cured at between 100 °C and 150 °C for 10 to 15 min.

After curing, the covalent bonds between the coating and polycarbonate interface provide adhesion and wear durability. The coatings provide low COF, enhanced UV durability, and a sWCA of 115°. The transmittance of the coated polycarbonate is very similar to uncoated polycarbonate at 905nm. The UVH coatings coated polycarbonate could maintain relatively high hydrophobicity throughout the 3000 hr test in WOM.

3. COATINGS CHARACTERIZATION TECHNIQUES

The static water contact angle (sWCA) of UVH coatings was measured using the Kruss DSA 100 instrument (KRÜSS GmbH, Hamburg, Germany). The procedure used to measure sWCA is to place a 2 µL drop of High-Performance Liquid Chromatography (HPLC) grade water on the substrate and measure the contact angle 3 times with 1 sec in-between measurements. This is repeated 3 times for a total of 9 measurements. An average is recorded. The transmittance of UVH coated polycarbonate samples were measured with Spectrophotometer LAMBDA 950 (PerkinElmer, Inc., Waltham, MA).

The UV durability of UVH coatings was evaluated with Ci5000 Weather-O-meter (Atlas Material Testing Technology, Mount Prospect, IL). The initial sWCA was recorded for coated and non-coated polycarbonate substrate, then the samples were placed in the WOM Xenon chamber using the ASTM D7869 method for 3000 hours. The samples were removed every 500 hours and measured sWCA and transmittance.

4. LIDAR PERFORMANCE WITH UVH COATINGS IN STATIC TESTBED

The sets of UVH coatings coated polycarbonate substrates along with non-coated substrates were further evaluated with a VLP-16 LiDAR sensor (Velodyne Lidar, Inc., San Jose, CA) in a static testbed with different simulated weathering conditions, including fog, rain, mud, and bug. During the test, the polycarbonate substrate was assembled to the front of the LiDAR unit as a secondary enclosure, and the simulated weathering conditions were then applied to the substrate surface. A stationary LiDAR target is set at a fixed distance to return the LiDAR signal. Three metrics were measured to evaluate the sensor performance, including the target distance, detection intensity of the target, and the total number of the returned laser dots from the target.

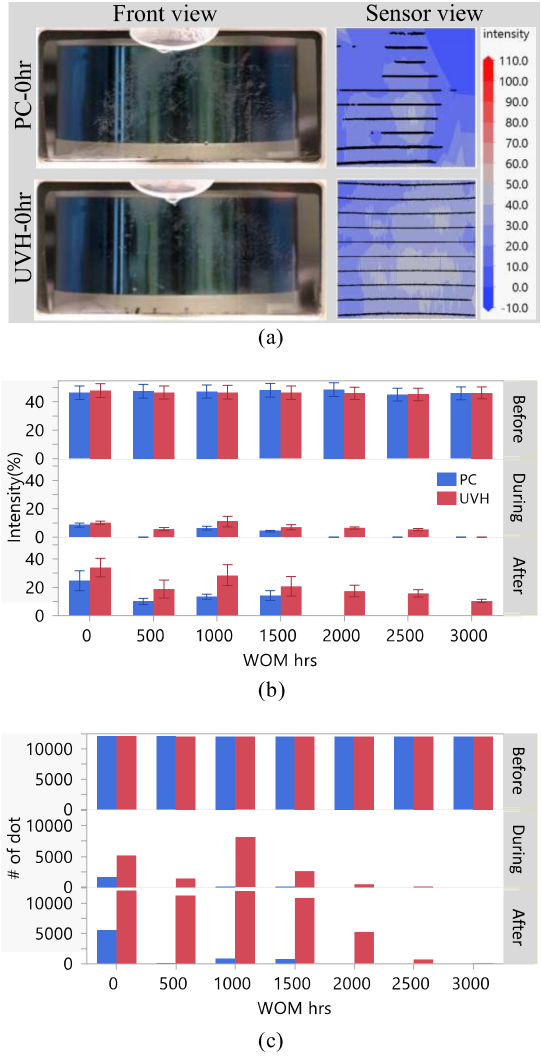
Figure 1. shows the LiDAR sensor performance under simulated fog conditions with uncoated and UVH coatings coated polycarbonate substrates. With the 0-hr WOM samples, the water droplets condensed on both uncoated and UVH coatings coated polycarbonate substrates and reduced the detection intensity of the target and the total

number of the returned laser dots. As shown in Figures 1(b) and 1(c) with UVH coatings, the LiDAR unit showed higher recovery of the detection intensity and returned laser dots after the fog condition stopped.

The LiDAR performance under simulated light rain conditions with the sample set is shown in figure 2. With the 0-hr WOM samples, the water droplets accumulated on the UVH coatings coated polycarbonate were smaller than the droplets on the uncoated substrates, resulting in higher detection intensity and more return laser dots.

Under both fog and rain conditions, the UVH coatings repelled and minimized the water droplets on its surface, and improved the LiDAR sensor detection intensity and the total number of returned laser dots.

A light mud mist that is to mimic the winter road condition was then applied to the sample set. Figure 3 shows the LiDAR performance under simulated light mud conditions with

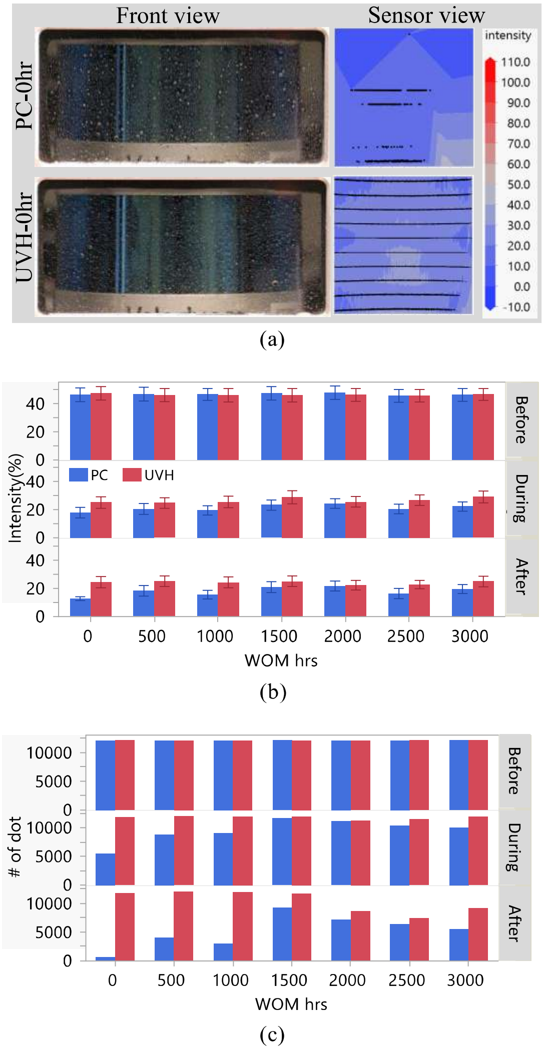


(a)

(b)

(c)

Figure 1: LiDAR under fog condition. (a) Comparison of sensor intensity with 0-hr WOM samples, (b) measured intensity, and (c) number of returning laser dots with 0-3000 hr WOM samples.



(a)

(b)

(c)

Figure 2: LiDAR under rain condition. (a) Comparison of sensor intensity with 0-hr WOM samples, (b) measured intensity, and (c) number of returning laser dots with 0-3000 hr WOM samples.

uncoated and UVH coatings coated polycarbonate substrates. During the light mud process, the UVH coatings coated polycarbonate showed higher intensity and more returned laser dots than the uncoated substrate. After the light mud condition stopped, the mud droplets accumulated on the UVH coatings coated substrate were much smaller than the uncoated substrate, resulting in higher detection intensity and signal strength.

After being tested with the mud condition, the samples were cleaned with IPA and DI water to remove the residue of the mud blend, then the samples were evaluated with the bug condition as shown in Figure 4. After the bug was launched on the surface of the polycarbonate it will partially block the view of the LiDAR. The majority of the bug on the UVH coatings coated polycarbonate can be removed after drying or blowing with compressed air.

Under both mud and bug conditions, the UVH coatings could maintain their hydrophobicity throughout the 3000-hr WOM and prevented dirt and bug from sticking to the sample surface.

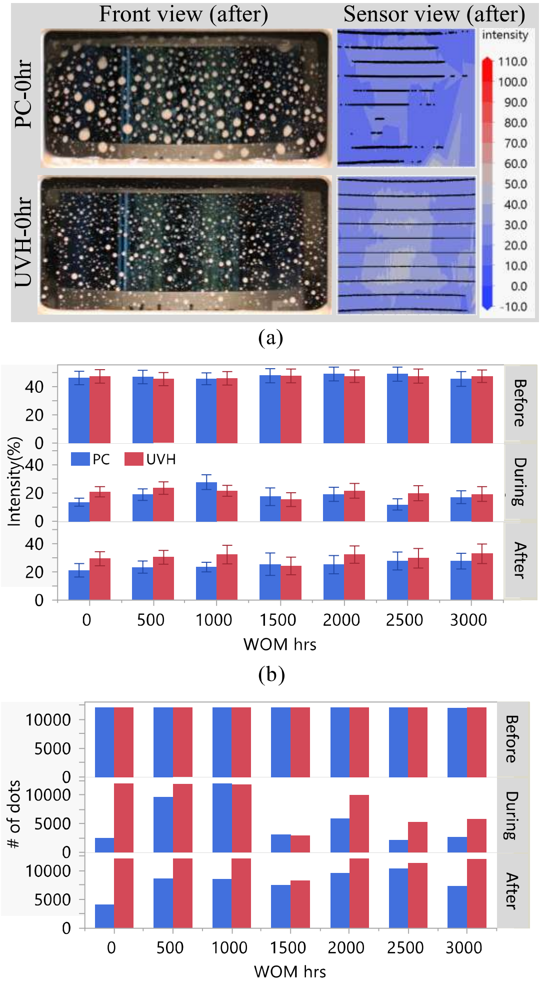


Figure 3: LiDAR under mud condition. (a) Comparison of intensity with 0-hr WOM samples, (b) measured intensity, and (c) number of returning laser dots with 0-3000hr WOM samples.

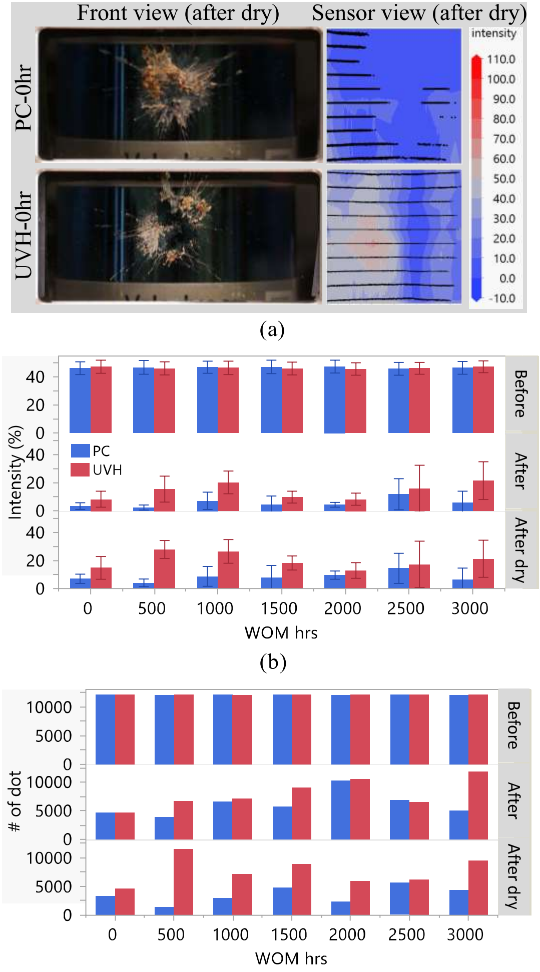


Figure 4: LiDAR under bug condition. (a) Comparison of intensity with 0-hr WOM samples, (b) measured intensity, and (c) number of returning laser dots with 0-3000hr WOM samples.

5. LIDAR PERFORMANCE WITH UVH COATINGS IN MOBILE TESTBED

The Mechatronics and Robotics Laboratory at North Dakota State University (NDSU) designed and built a robotic vehicle that can be used to test the efficacy of PPG coated samples for protecting robotic sensors in harsh environments under dynamic conditions when the robot is in motion. The electric-powered robotic vehicle equipped with a LiDAR has the ability to push or pull loads of up to 115kg (approximately 250 pounds), running at speeds of up to 5 meters per second.

The experiments consisted of running the robot in an area with artificial obstacles along with different simulated environmental conditions (Figure 5). Buckets of different colors and concrete foam tubes were used as artificial obstacles as shown in Figure 6.

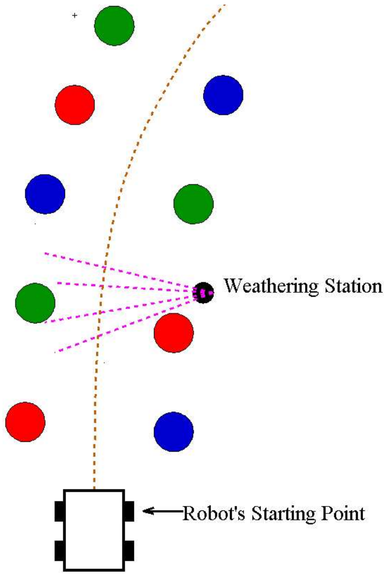


Figure 5: The experimental layout.

The experiments were limited to speeds of up to 2 meters per second only, which was programmed in the robot's speed controller. The sensor was only exposed to the simulated weathering for a short period of time and the sensor response over time was recorded. In all runs, the distance between the robot's starting point and the weathering station was fixed as 2.7 meters (approximately 3 yards), therefore, the weathering happened at the almost same time in all experiments.

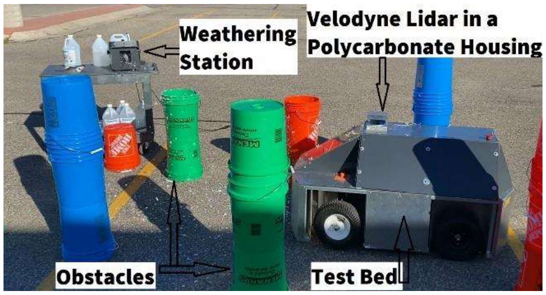


Figure 6: Robotic vehicle test bed and test track.

The LiDAR sensor on the robot was protected by polycarbonate substrates. The sets of substrates were provided by PPG Industries, one set of samples was coated by PPG's UVH coatings, and another set was uncoated. Specific environmental conditions that were tested include snowy conditions and muddy conditions.

Instead of continuously weathering the sensors as the robot runs, it was decided to weather them only once at the beginning as explained earlier, and then monitor their performance as time goes to determine how long they recover from these weather effects. The performance of the LiDAR was evaluated by its vision history, which is a record of the maximum distance recorded by the robot as it moves from the starting point to the end.

The LiDAR performance data was collected in a series of nine 16 × 2000 data matrices $D(t) = [d_{ij}]$ per second covering the robot's front view angle of ±10° at intervals of 0.01°. With such a massive amount of data per instant, it was decided to represent each matrix by its maximal singular value. The singular values of data matrices were simplified into four calculation steps on each matrix as follows:

The first calculation was to determine the mean value $\bar{x}(t)$ of each matrix

$$\bar{x}(t) = \frac{1}{mn}\sum_{i=1}^{n}\sum_{j=1}^{m}\mathbf{d}_{ij}(t)$$

The next calculation was to determine the standard deviation of each matrix, $s(t)$, where

$$s^2(t) = \frac{1}{mn}\sum_{i=1}^{n}\sum_{j=1}^{m}[\mathbf{d}_{ij}(t) - \bar{x}(t)(t)]^2$$

The matrix was then normalized where each element was recomputed as

$$n_{ij}(t) = \frac{1}{s(t)}[\mathbf{d}_{ij}(t) - \bar{x}(t)]$$

forming a new matrix $\boldsymbol{N}(t) = [n_{ij}(t)]$.

Finally, the data was reduced to a 16 × 16 matrix by the multiplication $N(t)N(t)^T$ and performed singular value decomposition of this reduced matrix such that if

$$\boldsymbol{N}(t)\boldsymbol{N}(t)^T = V\Lambda V^T$$

is the Eigen-decomposition of the reduced matrix, where V is its modal matrix, and Λ is the diagonal matrix of its eigenvalues $\lambda_1(t)$, $\lambda_2(t)$, $\cdots$, $\lambda_{16}(t)$ then the maximal singular value

$$\mu(t) = \left|\sqrt{\max\{\lambda_1(t), \lambda_2(t), \cdots, \lambda_{16}(t)\}}\right|$$

was used as a vision power for the LiDAR.

Figure 7 shows the response of the LiDAR sensor under heavy snow, which was splashed to the sensor at the robot at about 30 seconds for both the coated and uncoated substrates. In the reported experiments, the LiDAR had a maximal singular value of around 25 m. In both cases, the sensor lost vision immediately after being weathered. However, the sensor was able to recover from this blindness very fast in about 1 minute when it was protected by PPG coated substrates than the case when it was protected by uncoated substrates, which took almost 4 minutes to recover.

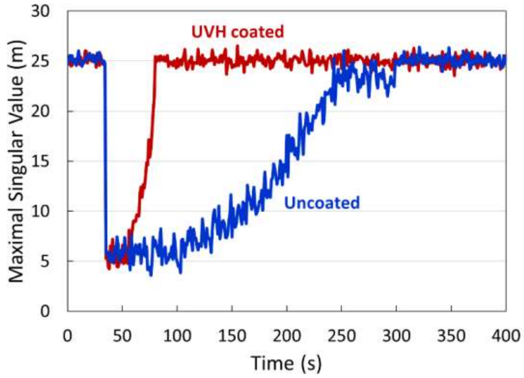


Figure 7: LiDAR response to heavy snow.

This trend was observed also for the case of muddy environments although the recovery time was a little longer than in snowy environments. Figure 8 shows the response to heavy muddy contamination; light mud response is not shown because it is in between Figure 7 and Figure 8. Results of Figure 8 show that the sensor protected by coated sheets recovered in about 3.5 minutes only compared to more than twice that time for the uncoated sheets.

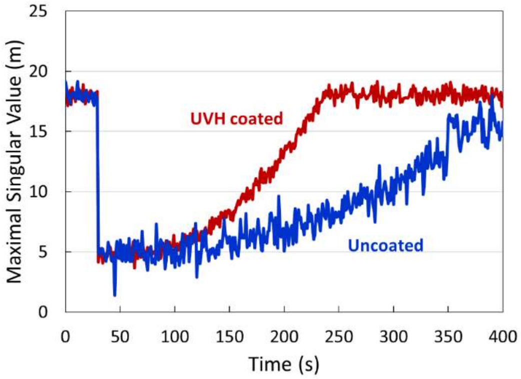


Figure 8: LiDAR response to muddy environment.

Although the exact recovery times depended also on other operating conditions such as the road terrain, vehicle speed, and ambient conditions, it was in general seen that under the same operating conditions, the LiDAR recovered faster when protected by

UVH coated polycarbonates than when they were plain.

6. SUMMARY

UV durable Hydrophobic (UVH) coatings were developed to improve LiDAR performance in challenging operating conditions. This hydrophobic coating exhibited high optical transmission with good wear durability and excellent UV durability by passing the 3000-hr WOM test. The UVH coatings coated polycarbonate substrates along with non-coated substrates were further evaluated with a VLP-16 LiDAR sensor using a static lab testbed and a mobile testbed under various simulated weathering conditions (fog, rain, snow, mud, and bug). The results indicated that UVH coatings could repel or minimize the water droplets and prevent dust and dirt from sticking to the lens surface, recover from the weather effects faster than the uncoated substrates.

These UVH easy-to-clean coatings with high optical transmission, good wear durability, and excellent UV durability could improve the effectiveness and efficiency of the LiDAR sensor, which provides a key improvement in safety for autonomous vehicles.

7. ACKNOLEDGEMENT

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